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Design of Photovoltaic Power System for a Precursor Mission for Human Exploration of Mars

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***Abstract* — This project analyzed the viability of a photovoltaic power source for technology demonstration mission to demonstrate Mars in-situ resource utilization (ISRU) to produce propellant for a future human mission, based on technology available within the next ten years. For this assessment, we performed a power-system design study for a scaled ISRU demonstrator lander on the Mars surface based on existing solar array technologies.**

***Index Terms* — solar power generation, photovoltaic cells, Mars.**

I. Introduction

NASA's Advanced Exploration Systems (AES) Modular Power Systems (AMPS) project aims to develop and infuse new power system and component technologies for exploration based ground demonstrations and to assess design concepts for future flight missions. One of the goals of this project was to analyze the viability of a photovoltaic power source for technology demonstration mission to demonstrate Mars in-situ resource utilization (ISRU) to produce propellant for a future human mission, based on technology available within the next five years. For this assessment, we performed a power-system design study for a scaled ISRU demonstrator lander on the Mars surface based on existing solar array technologies [1]. As a figure of merit, the power requirements for the system are derived from the ISRU plant's need to demonstrate the production of 4400 kg of liquid oxygen at a minimum rate of 0.45 kg/hr. The assessment resulted in the design of a lander consisting of four lightweight solar arrays, providing up to 16 kW of power. Details on the use of solar power on the Mars surface for the ISRU demonstration are presented here.

II. CASES

Three cases were assessed for operation of the ISRU plant by solar power with an emphasis on demonstrating the production rate while reducing mass, reducing production time, and maintain operation in the Martian environment. A landing site of 2 degrees south of the equator was selected for all cases due to its uniformity of daylight throughout the year. A 120 day power-down of the ISRU plant was incorporated in all cases due to the potential for a global dust storm. Solar cell and array technology is also consistent across the three cases.

The baseline case (Case 1) is operated at the required rate for liquid oxygen production of 0.45 kg/hr. needed to demonstrate the functionality of the ISRU system during the daytime. In this case, the system goes into a standby mode every evening. This requires that the ISRU plant be capable of being cooled down and warmed back up every day.

Case 2 produces oxygen at the required rate but is augmented by batteries to allow for continuous operation of the ISRU plant. This configuration eliminates the need to power down the ISRU plant (except in the case of the major dust storm) and would shorten the amount of time needed to demonstrate the ability to produce the amount of liquid required. The addition of the batteries will cause the solar arrays to be larger due to the need to both run the ISRU plant and charge the batteries during the daytime.

For Case 3 we looked back at daytime only production but doubled the production rate to 0.9 kg/hr of liquid oxygen. This case would bring down the overall time to produce the necessary amount of oxygen but would also require additional ISRU components and larger solar arrays. This case still has the potential problem of cycling the ISRU plant off daily as in Case 1.

III. DESIGN ASSUMPTIONS

In an effort to make the study as realistic as possible, the assessment utilized technology that is either currently available or projected to be in the next 5 – 10 years. Assumptions were made as to the availability and extensibility of some technologies but no major advances were considered. As much as possible, lander components were not modified between each power system trade. Components related to the power system included energy storage, thermal and radiation protection, and power system structural supports were considered and included in the assessment.

There are possibly multiple solar array structures that could fulfill the needs of the ISRU demonstrator but due to the limited timeframe for this assessment a down select to one technology was necessary. The rationale for this selection was to utilize a solar array that could be deployed by its own mechanisms and not require robotics or complex undemonstrated methods for deployment. Additionally, the array needed to be very compact when stowed and have the capability of resisting the Martian wind loads. The Orbital ATK Ultraflex has been successfully demonstrated on Mars (although at a modest diameter) with the Mars Phoenix lander and is also to be used with the Mars Insight lander, both which have exposure to these wind loads. The characteristics of the Ultraflex solar array for the Mars surface power application is based on work by ATK which shows the capability of their design at various diameters and loading levels [2]. The data presented by ATK include curves of point designs based on their detailed models for acceleration loads of up to 2.7 g and voltages up to 120 V assuming various kind of solar cell technology. For these designs, higher voltage is beneficial to reducing overall system mass, so the 120 V point designs were used. The point designs using the 2.7 g high acceleration loads (originally based on spacecraft propulsive loads, but indirectly applicable to Mars wind loads) were used to utilize the extreme structural capability of the Ultraflex structures that are needed for a wind loading environment. It has been shown subsequently that the Ultraflex structures can be designed for even higher g loads if desired (e.g. Cygnus 5 g loads for ISS loads). Inverted metamorphic multijuction (IMM) solar cells (33% conversion efficiency at 1 AU and 28°C) were also selected to minimize mass and obtain more performance than conventional state of the art triple junction cells which were used on the earlier Mars landers [3].

The solar arrays for the ISRU demonstrator were sized based on insignificant radiation degradation and only a thin coverglass is assumed to be required. Two axis gimbals are included to improve power generation via pointing for sun tracking and to assist in dust removal. The gimbals were scaled based on the mass of the solar array they must support and were from CEV Orion designs which were capable of 2.7 g TLI acceleration loads. On the Martian surface, the IMM cells are expected to have a 30% conversion efficiency including spectral losses from the atmosphere. The packing density of cells on the Ultraflex array is was set at 73%. After initial deployment a 5% permanent dust power loss is added to the assumption with more accumulated dust removed periodically. It is also assumed that the system have 4 solar arrays equally spaced around the lander to make best use of available area and balanced for the lander.

During a 120 day dust storm, we assume no ISRU production. Based on MER-B dust storm data [4]–[7], the optical depth goes from the baseline 1.0 to a worse case value of ~5.0. The incident energy on the solar array would be 35% of the baseline design used in sizing. The solar arrays provide power only to housekeeping loads during the dust storm. The duration and intensity of most dust storms are not expected to be as severe as the worst case scenario estimates used in this study. In practice, the system would be placed into the dust storm standby mode when daily solar intensity flux reaches a set minimum point. The system would go into full production mode when the daily flux increases above that point.

The following is a list of key parameters considered for this assessment in determining the proper sizing of the solar arrays to meet the ISRU plant production requirements:

- 120 V to main ISRU load, 28 V nominal bus for spacecraft housekeeping loads
- 120 V lightweight array using IMM cells
- 4 wings, designed for 2.7 g (to allow for operation under Mars gravity and wind loading).
- ATK Ultraflex arrays integrated with two axis gimbals
- Tracking is beneficial for low optical depths, also required for dust removal.
- Cells 33% efficient at BOL, 28°C, AM0; 30% at Mars surface, 73% packing factor.
- Assumed no radiation degradation
- Mars at average distance= 1.52 AU
- Optical depth = 1; (calculated atmospheric dust power solar attenuation factor = 0.68) [8]
- Dust storm optical depth = 5 (calculated atmospheric dust power solar attenuation factor = 0.24)
- Settled dust is removed via two axis gimbal articulation (Dust power loss factor = 0.95) [9]

IV. CASE RESULTS

In general, the three solar power cases for the ISRU demonstrator appear similar in layout. The lander consists of the ISRU plant, propellant storage, batteries, and four solar arrays mounted around the circumference. The solar arrays are stowed against the lander for launch and flight and would autonomously deploy after landing. The stowed configuration for Case 1 is shown in Figure 1. A concept of operations (ConOps) was conceived for each case and is presented below. The ConOps is notional for each case and the dates are provided for demonstrate the amount of time needed to operate the ISRU plant.

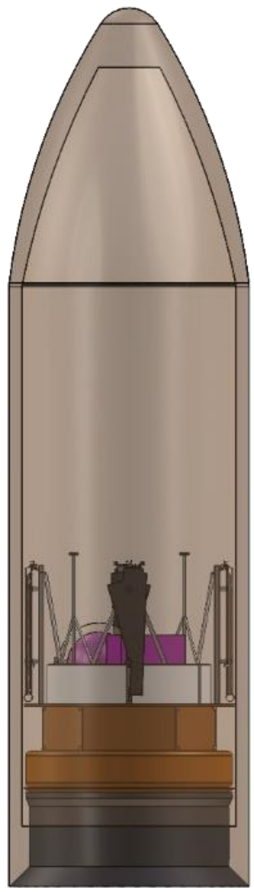

Fig. 1. ISRU plant in stowed solar array configuration for Case 1. The solar arrays are stowed and spaced around the lander. The launch vehicle is a Delta IV Heavy.

The requirements for Case 1 were met by using four 5.6 meter diameter Ultraflex arrays with two axis gimbals (Figure 2). This configuration would operate for 10 hours per day and produce liquid oxygen at the required 0.45 kg/hr. rate. The production time is limited to 10 hours per day due to the ISRU plant needing to warm up slowly from its overnight standby state. At this rate, it would take approximately 1100 days to produce the required 4400 kg of liquid oxygen. As designed, the system would store 1500 kg while the rest of the produced oxygen is vented. The ability to demonstrate storage of the produced oxygen was required but the amount to needed to be stored was not specified. A value of 1500 kg was used as an arbitrary point of demonstration. A ConOps showing key mission phases is shown in Figure 3. The dust storm is expected to occur at some point during oxygen production at which point the ISRU would be put into a standby state similar to what it does during the Martian night. During the dust storm, stored oxygen is expected to boil off.

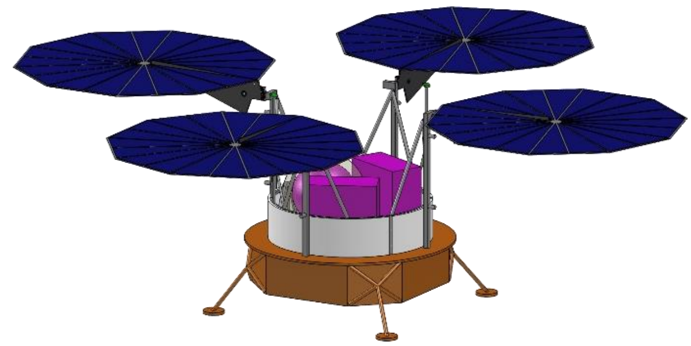

Fig. 2. Case 1 lander with 5.6 meter diameter Ultraflex solar arrays. The arrays have the ability to tilt up for 45 degrees both for sun tracking and for dust mitigation.

This case is designed for daytime only production with the ISRU system cycling off daily. It was assumed for this case that the plant is capable of being cycled on and off this often which may turn out to not be practical. The mass for the solar arrays in Case 1A is a total of approximately 120 kg. The mass of the lithium ion batteries used provide standby power to restart the ISRU plant each morning is approximately 100 kg. For this production rate, the ISRU system mass is projected to be 163 kg.

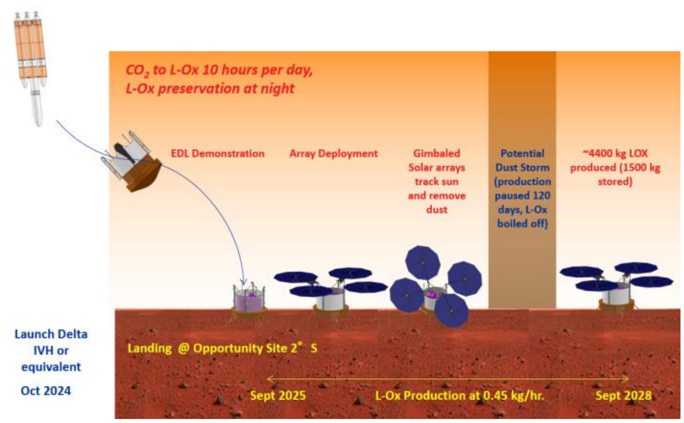

Fig. 3. ConOps for Case 1. It would take approximately 3 Earth years to successfully demonstrate the ISRU system.

In Case 2, the ISRU plant operates continuously throughout the Martian day and night. The production rate is the same as in Case 1 at 0.45 kg per hour but is not limited to 10 hours each day. To run continuously, the solar arrays needed to be increased and significant energy storage needed to be added to the lander. The solar arrays need to be large enough to run the ISRU plant during the day and charge the energy storage system with enough power to run throughout the night. This resulted in needing four 7.5 meter diameter solar arrays which have a mass of approximately 260 kg. The solar arrays are shown in Figure 4 as compared to those of Case 1. The batteries would add an additional 900 kg. Since the ISRU plant is the same, its mass remains at 163 kg. The ConOps for Case 2 is shown in Figure 5. Here the 4400 kg production requirement is met in approximately 530 days. The same amount of oxygen is stored but would not necessarily be vented during the dust storm like it was in Case 1. The larger solar arrays and energy storage would likely allow for the oxygen to be maintained during the dust storm.

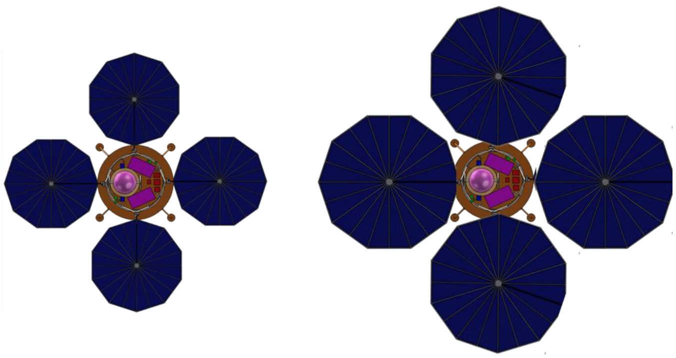

Fig. 4. Comparison of solar array sizes between Case 1 and Case 2. The size of the lander is the same in both cases.

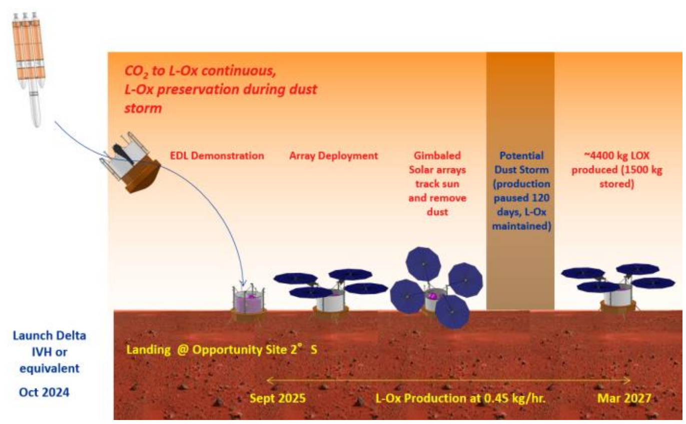

Fig. 5. ConOps for Case 2. Additional batteries have been added to the lander to allow for continuous production and for storage during the dust storm.

Case 3 is similar to Case 1 in that the ISRU plant is allowed to cycle on and off daily, but here the production plant has a doubled capacity to allow for a production rate of 0.9 kg per hour of oxygen. The amount of oxygen produced and stored is the same as the previous cases. At this higher rate, the production is achieved in approximately 610 days. This system is met by using the same four 7.5 meter diameter arrays as Case 2 and the 100 kg of batteries similar to Case 1. The mass of the ISRU plant is increased to approximately 284 kg which allows for the doubled production rate.

This case has similar ConOps to Case 1 in that it would be cycled on and off daily. However, the larger solar arrays would provide sufficient power during the dust storm to maintain storage of the oxygen during the dust storm. The practicality of cycling the ISRU plant daily is still a concern for this case.

Table 1 provides a comparison between the cases considered in this study. Although the arrays are larger and the full system much heavier, Case 2 has the advantage of limited cycles between standby and production of the ISRU plant and the shorter overall time to demonstrate the required production metric. However, Case 1 does have the smallest mass and would be the least expensive option to build and launch. If the cycling between standby and production is negligible or can be mitigated, then Case 1 would be the most likely candidate.

V. CONCLUSIONS

This assessment considered a solar array option for use on an ISRU demonstration mission as a precursor to a human crewed mission on the surface of Mars. The assessment was performed over the course of five weeks and provided a snapshot of a possible technology solution for this mission. Within these cases, it was shown that solar power may be a viable option for meeting the mission requirements dependent on many factors including the mission location and our current understanding of the ISRU plant at both the demonstrator and the full scale sizes.

This study is based on the power and storage needs of a concept ISRU plant available at this time. The ISRU plant has nominal component detail at this time and additional full system details are needed to better refine and help validate this assessment. Namely, the ability of the ISRU system to be cycled between standby mode and production mode multiple times during its operation needs to be addressed. Additionally, the thermal support systems considered were quite large assuming that cryocooler atmospheric collection systems are used. Multiple technology advances were expected which benefited the assessment. Higher efficient solar cell and improved battery performance would be required to make full use of solar arrays for a potential human crewed mission.

TABLE I

RESULTS OF CASE COMPARISONS

	Case 1	**Case 2**	**Case 3**
Description	Single ISRU Plant, Daytime Production	Single ISRU Plant, Continuous Production	Dual ISRU Plant, Daytime Production
ISRU, Power, Thermal, Avionics, Mechanical Mass (w 30% growth)	1116 kg	2396 kg	1507 kg
Available Power	~8 kW	~16 kW	~16 kW
Solar Array Size	Four 5.6 m diameter	Four 7.5 m diameter	Four 7.5 m diameter
Solar Array Mass	120 kg	260 kg	260 kg
Battery Mass	~100 kg	~900 kg	~100 kg
ISRU System Mass	163 kg	163 kg	284 kg
Daily Production of O2	4.5 kg	10.8 kg	9.0 kg
Days to Produce 4400 kg of LOX	1098	527	609
ISRU System Standby / Production Cycles	1098	<5	609

It is suggested that future assessments explore the impacts on the system of higher latitudes and fixed angle arrays. The ISRU plant needs further refinement and a point design should be performed at the system level to better provide integration with demonstrators and future Mars missions. This would include exploring alternate atmospheric collection devices and more optimal radiator layouts. It is also understood that any changes to the launch vehicle or the lander system would necessitate changes to this design and should be considered. Additionally, it is recommended that estimates for dust storm duration, optical depth, and frequency based on location and seasonal effects is understood and that a better definition of dust parameters in terms of accumulation on surfaces and removal is defined.

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